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An Average Charge Detector for Mass Spectrometers

John Dimeff, Albert Lieber, and Clifford Burrous

Introduction

Information regarding the magnitude of the low-energy solar plasma flux as a function of energy-to-charge ratio has been obtained by a series of experiments within the Earth's magnetosphere, and in cis-lunar space (Refs. 1-8). Additional experiments have made measurements in interplanetary space. Theoretical evidence based on abundance arguments and the recent experimental results showing two distinct intensity peaks in the energy-to-charge spectra suggest that the solar plasma is a stream of fully ionized hydrogen and helium with slight admixtures (perhaps 0.9%) of the heavier elements and helium in other ionization states (He^+). The data indicate, further, that the hydrogen-to-helium ratio is not stable, but fluctuates rapidly in magnitude and is probably influenced by solar activity. In general, during periods of low solar activity, peaks corresponding to hydrogen and helium are separable outside the magnetosphere using conventional electrostatic plasma probes. However, during periods of high solar activity and in the turbulent region of the magnetospheric boundary these peaks merge. Since the mass-to-charge ratios and velocity distribution for these two principal components of the solar plasma are such that their energy-to-charge distributions overlap, unambiguous measurements of the plasma characteristics cannot be obtained with instruments currently in use. Even though helium ions account numerically for perhaps only 10% of the solar wind, by virtue of their greater mass they account for approximately 40% of the mass of the solar wind. Thus, the hydrogen-helium ratio must be accurately determined before any calculations can be made testing theories on the behavior of the solar wind.

The ambiguity in the measurements made with present space borne plasma analyzers is inherent in the nature of the instruments themselves. In most forms of the "plasma analyzer", the unknown ion stream first passes through one or more separators which deflect, intercept, or bunch the ions by means of either an electrostatic or an electromagnetic force. Since the separator is differentially sensitive to some combination of the mass, charge and velocity of the ionized particle, it introduces a "filtering" action which allows only those particles within a certain spectral window to impinge on a collecting plate at the exit of the filter. The current measured at the collecting plate is proportional to the beam intensity integrated over the spectral window, where the selective parameter is $\frac{1}{2}\frac{mv^2}{q}$ for the electrostatic separator, $\frac{mv}{q}$ for the magnetic separator, and v for the time-of-flight or $\vec{E} \times \vec{B}$ separators. It is clear that the only parameters that can be defined unambiguously by using combinations of these filters are the mass-to-charge ratio and the velocity. An experiment is required, then, which can provide an independent measurement of either the mass or the charge of the particle. By the addition of a small instrument to many of the analyzers currently in use, it is possible to obtain a measurement of the average charge of the ions in the plasma. If the estimates of the stream composition are valid, this would provide a first approximation of the hydrogen-to-helium ratio. The purpose of this paper is to describe an instrument capable of providing this measurement and to present preliminary results it has provided in the laboratory.

Description of Instrument

The current collected at the exit of a "mass analyzer" is the sum of the number of charges deposited per unit time by each of the constituents of the plasma stream. That is

$$i_c = \sum_{x=1}^{\infty} n_x q_x = N\bar{q}$$

where n_x is the number of ions collected per unit time of the xth constituent, q_x is the charge carried by each ion of the xth constituent, N is the total number of particles collected per unit time, and $\bar{q}$ is the average charge per particle. Since the solar plasma can be assumed to be primarily a mixture of protons ($q_1 = +e$) and alpha particles ($q_2 = 2\ e$) with only traces of other elements, it can be assumed that

$$i_c \approx q_1\ (n_1 + 2\ n_2)$$
$$N\bar{q} \approx q_1\ (N + n_2)$$

The value of the helium fraction in the ion stream is, then,

$$\frac{n_2}{N} = \frac{\bar{q}}{q_1} - 1$$

The measurement of i_c is routinely obtained in the plasma analyzer and, therefore, presents no problem. The only problem, then, is the measurement of $\bar{q}$. This measurement is obtained by allowing a small fraction of the ions incident on the collector plate to pass through a small hole in that plate and be counted by a device similar in function to a conventional multidynode electron multiplier. The total number of ions incident on the collector plate per unit time is obtained by multiplying the number counted per unit time by an "effective" area ratio; and the average charge is obtained by dividing the collector plate current by the number of ions incident on the collector per unit time.

Measurements were obtained in the laboratory with the apparatus shown schematically in Figure 1 and photographically in Figure 2. The incoming stream of charged particles is obtained from the output of a Nier magnetic analyzer and is further analyzed by passage through a pair of cylindrical electrostatic separator plates. At the exit of the separator plates, an aperture limits the beam to a well-defined area; those ions impinging outside that area being neutralized and pumped out of the system while those within that area are allowed to continue in motion parallel to the axis of a "drift tube" maintained at ground potential. Most of these ions pass through a second aperture within the drift tube and strike a collector plate. A negative potential applied to a ring located between the second aperture and the beam collector plate suppresses the secondary electrons ejected by the impact of the positive ion on the edge of the second aperture or on the collector plate. The ring is so designed that it is not struck by the ion beam. Data relating the total current to the suppressor voltage are presented in figure 3 and demonstrate that the total collector current measured by the electrometer is a true measure of the incident ion current, and need not be corrected for a secondary electron emission current if suppression voltages are more negative than -40 volts.

A small number of the ions incident on the face of the collector plate pass through the small "ion counting aperture" in the collector plate and strike the open end of a distributed electron multiplier (Refs. 9-10). The output of the electron-multiplier is shaped by means of a resistance and capacitance network and fed into a counter. Background count recorded by the counter when no beam was incident on the Channeltron was less than 2 counts per minute.

In theory, accurate measurement of the current, collector plate area, counting hole area, and number of ions counted should provide a direct determination of the average charge, $\bar{q}$, of the ions incident on the analyzer. There are, however, several factors which limit the accuracy of such a determination. These factors will be considered sequentially in the para-

*~~Manufactured by Bendix Research Corp. - - and marketed under the name of "Channeltron".~~

graphs below.

Current was measured with a Cary (Applied Physics Corporation, Model 35) portable electrometer, calibrated before and after each experimental run by comparison with a Picoampere Source (Keithley, Model 261). Specified short-term accuracies for the two instruments are $\pm 1\%$ of full scale and $\pm 0.6\%$ of full scale respectively. Calibration data indicate a comparative reading error of approximately 5%, with an average deviation of relative readings of $\pm 0.7\%$. Because even minor instabilities of the ion beam can affect the experiment, the output of the electrometer was integrated by a current integrator activated for the period during which the ions are counted. Measured currents are corrected for the leakage current caused by the application of the suppressor voltage across the imperfect (2×10^{17} ohm) insulator separating the suppressor from the collector.

The collector plate area is defined by two circular apertures of 0.1-inch diameter located at the entrance and the exit of the drift tube. The accuracy with which it is defined, however, is limited by uncertainties in the ion trajectories. While the separation of the instrument from the source is sufficiently great to insure parallel ion trajectories, two factors introduce dispersion of the ion beam: the electrostatic lens effect at the entrance and the exit of the electrostatic analyser; and the dispersion of the beam resulting from the effect of the electrostatic analyzer on the various components of the multi-energetic ion stream.

The counting hole aperture used in the experimental apparatus is 0.0012-inch diameter. While this measurement is known within a few per cent, two uncertainties are introduced in the effective area which are of considerably greater magnitudes. First, since the current density of the beam impinging on the collector plate cannot be assumed to be uniform, the effective area of the counting aperture should be corrected to account for the ratio of current density at the counting hole to the current density averaged over the collecting plate. Some indication of the possible magnitude of this effect is obtained by reference to figure 4 which shows the variation in the measured value of the average charge that results from the magnetic field used to select the ions at the source and from varying the voltages applied to the plates of the electrostatic analyzer while illuminating the entrance port with a constant beam.

The second important correction needed to determine the effective counting hole area is related to ~~the efficiency of the process by which the incident was producing secondary electrons in~~ the counting device. The device used in the experiment was a hollow glass tube bent into a circular arc and internally coated with a resistive film. An ion incident on one open end of the multiplier causes the emission of secondary electrons. Under the action of a voltage field applied along the tube, these electrons cause a cascading group of secondaries to drift toward the output end of the tube. The pulse of electrons caused by each such event is collected by a cup, maintained at a potential of +100 volts relative to the output end of the multiplier. Under the conditions described, the effective gain of the electron multiplier was approximately 3×10^7. While the recorded background count for the device was essentially zero, lack of information on the magnitude or stability of the process by which secondary electrons are produced by various ions at the entrance of the tube prevents any accurate determination of the "effective" counting hole area.

Errors associated with the statistical variance (due to the limited number of ions counted) can generally be kept small by using counting time intervals sufficiently long to allow accumulation of large numbers of counts. Errors associated with counter-circuitry are generally due to "pile-up" (an additive deposit of charges due to nearly simultaneous current pulses) or "depletion" (an inability to count an incoming pulse until the device recovers from a depleted charge state caused by previous pulses). In order to determine whether such errors exist and to establish their magnitude, a pulse height spectrum was obtained for data collected during a one minute run using a counting rate of 22,170 counts per minute (Fig. 5). The complete absence of a double amplitude peak in the pulse height spectrum indicates that the pile-up error was non-existent for the experiments described or that current saturation occurs in the channel multiplier. Photographs of the output pulse from the resistance capacitance shaping network used in obtaining the data of Figure 5 are shown in Figure 6, and indicate that the current pulse collected at the output of the channel multiplier is approximately .06 μ sec. in duration. Considering this duration and the pulse rate being used, it is evident that "pile-up" errors should indeed be negligibly smaller independently of whether or not current saturation exists.

The existence of depletion errors is evident, however, from the fact that a significant number of small amplitude pulses was recorded. This effect was probably caused by the fact that a current pulse changes the voltage distribution along the continuous channel electron multiplier by depleting charge on the capacitance distributed between the various segments of the multiplier and ground. Since the resistance of the thin film device is high, the voltage distribution and, therefore, the gain of the multiplier is affected for a finite time after each such occurrence. While depletion errors are not completely negligible, it is to be noted that even if all pulses below half amplitude were not counted, the error (227 counts) is approximately one percent.

Results

Using the equipment described and the measured area ratio, a charge determination experiment was performed on a 6 Kev beam of ionized atomic hydrogen. Thirty separate runs were made at various beam current levels. The data indicated a charge of 1.271×10^{-19} coulombs per particle with an average deviation of $\pm 0.012 \times 10^{-19}$ coulombs per particle. These indicate that the charge per particle should be multiplied by a factor of 1.258 in order to obtain the actual charge of the proton. The measured area ratio should be corrected by the same factor, then, to obtain an effective area ratio which includes all absolute errors in the instrument and the accessory equipment. The corrected charge data for hydrogen are shown in Figure 7 along with the one sigma statistical error envelope (shown by the dotted lines). Variation in measured charge per particle as a function of beam current was essentially zero for the current range from 10^{-13} to 4×10^{-12} amperes.

A similar experiment was conducted on a 6 Kev beam of doubly-ionized He_3. The charge per particle was computed using the "effective" area ratio obtained from the previous runs with H^+. The charge per particle, averaged for a total of twenty-two runs at various current levels was 3.217×10^{-19} coulombs. Average deviation of the data was $.093 \times 10^{-19}$ coulombs per particle -- as compared to the $+.013 \times 10^{-19}$ coulombs per particle absolute error in the average charge measurement. The individual data points together with the one sigma statistical error envelope introduced in the measurement because of the limited number of particles are shown in Figure 7.

In order to determine whether the charge per particle measured by the instrument is affected by the energy of the incoming beam, several runs were made with incoming beams of H^+ and He_3^{++}. A minimum of four runs each were made at energies of 4 Kev to 20 Kev at increments of 2 Kev. Data from those experiments are presented in Figure 8. It is to be remembered that the diameter of the beam was not large compared to the diameter of the experiment, that Figure 4 indicates both a nonuniformity of the beam and a sensitivity to the adjustment of the experimental apparatus; and that data corresponding to Figure 4 were not obtained for energies other than 6 KV. Because of these equipment limitations, it is felt that the effects of energy on measured charge to be noted in Figure ~~X~~ 8 are not clearly assignable to the instrument but are possibly introduced by undetermined effects in the test apparatus and proceedures.

Discussion

The performance of the average charge detector described above is entirely adequate for early space experiments to determine the hydrogen-to-helium ratio in the solar plasma. In its present form, the accuracy of the equipment is somewhat limited because of errors related to beam non-uniformity. One portion of this error (the part related to limited dimensions of the source) would be essentially eliminated in the actual application which involves total immersion of the equipment in a plasma stream of dimensions much greater than those of the experimental equipment. The second portion of this error (that part introduced by the effect of fields within the instrument) would be eliminated by using a large number of small diameter counting apertures uniformly distributed across the surface of the collector plate. Additional errors due to depletion effects in the electron multiplier were made relatively small by using a mounting geometry which minimized stray capacitance, but could be reduced further by employing a distributed, driven shield located on the outside of the multiplier.

It is expected that improvements of the type discussed would decrease errors in the measurement of average charge to the order of a fraction of one percent.

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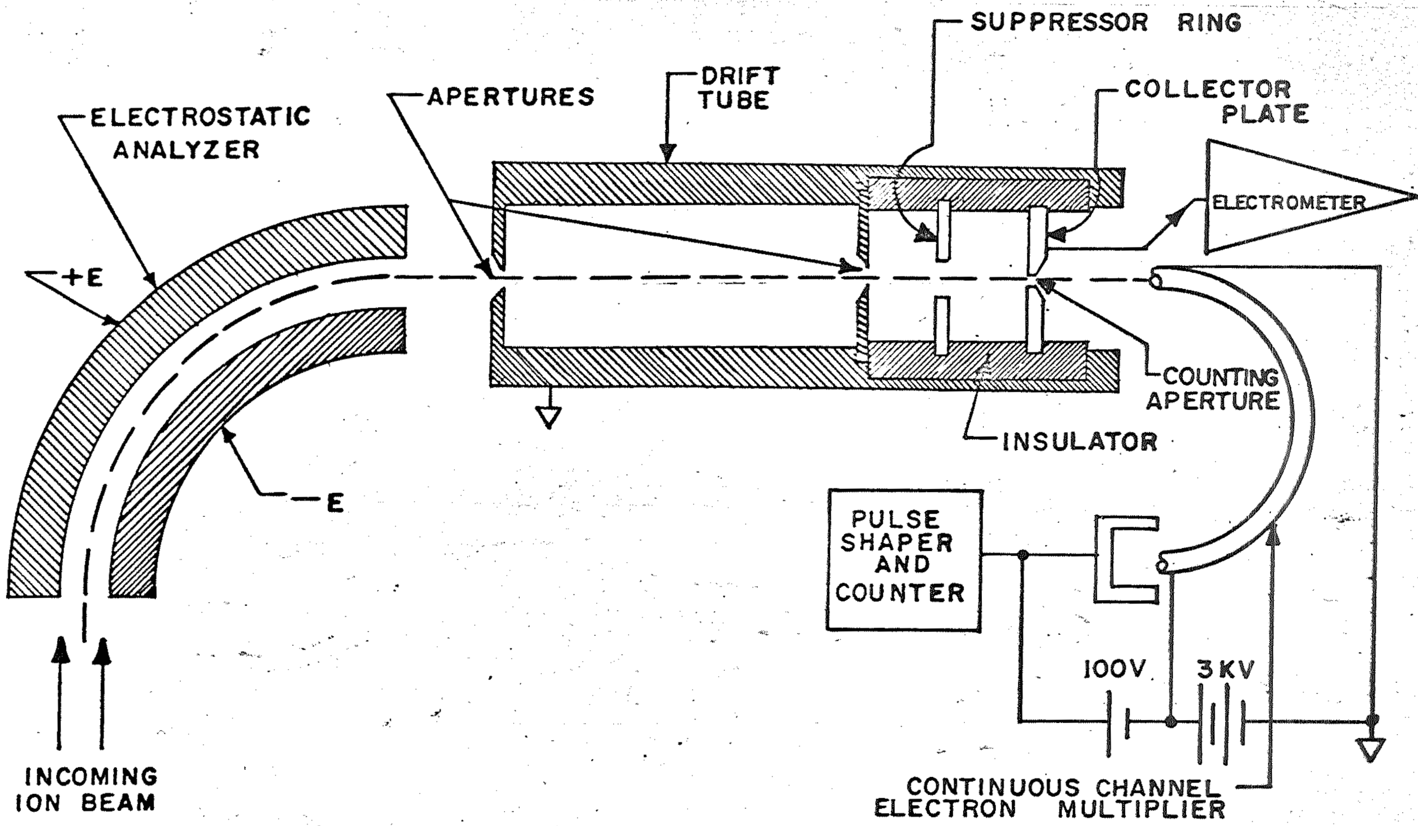

FIG. I SCHEMATIC DRAWING OF PLASMA ANALYZER WITH AVERAGE CHARGE DETECTION CAPABILITY

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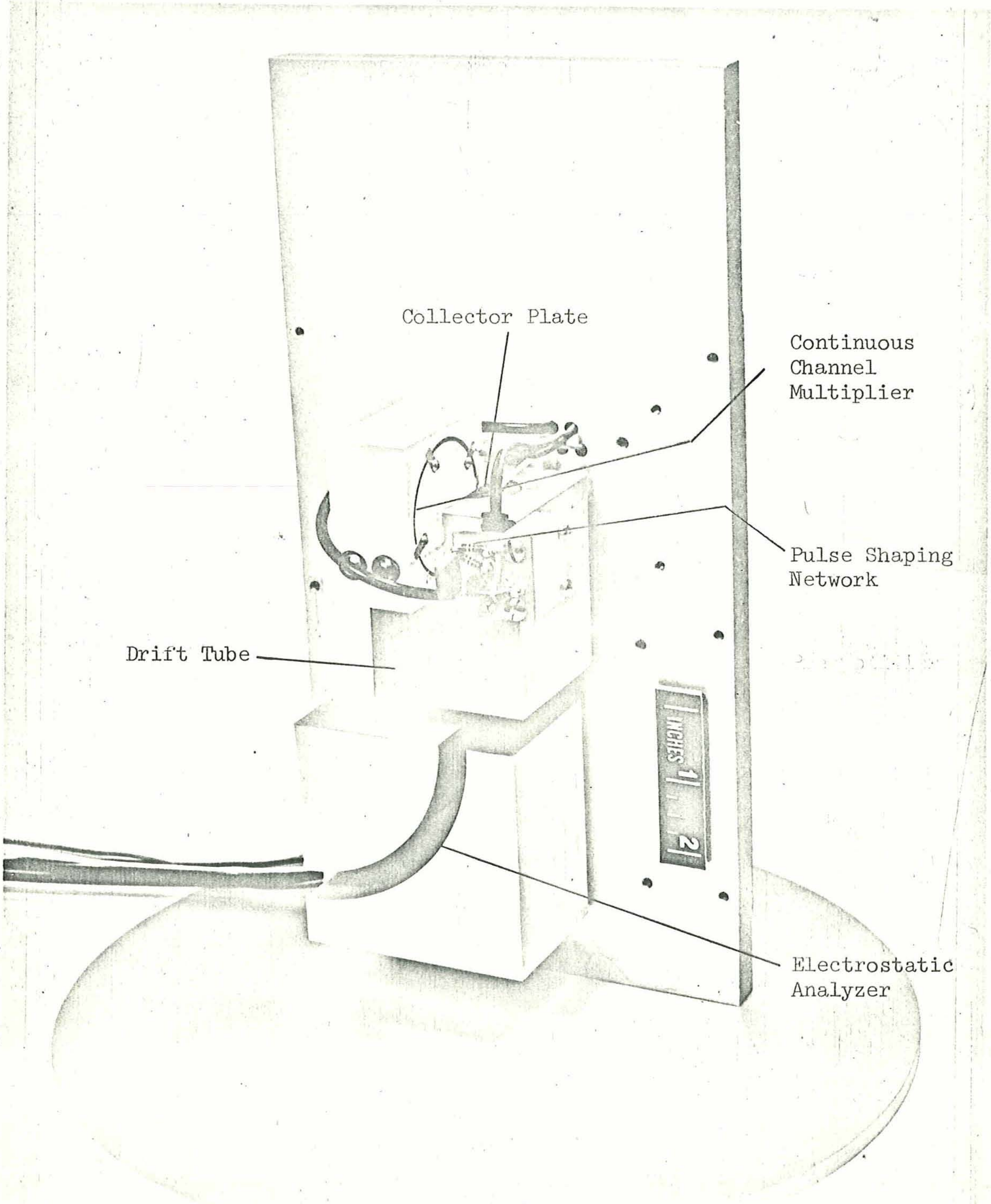

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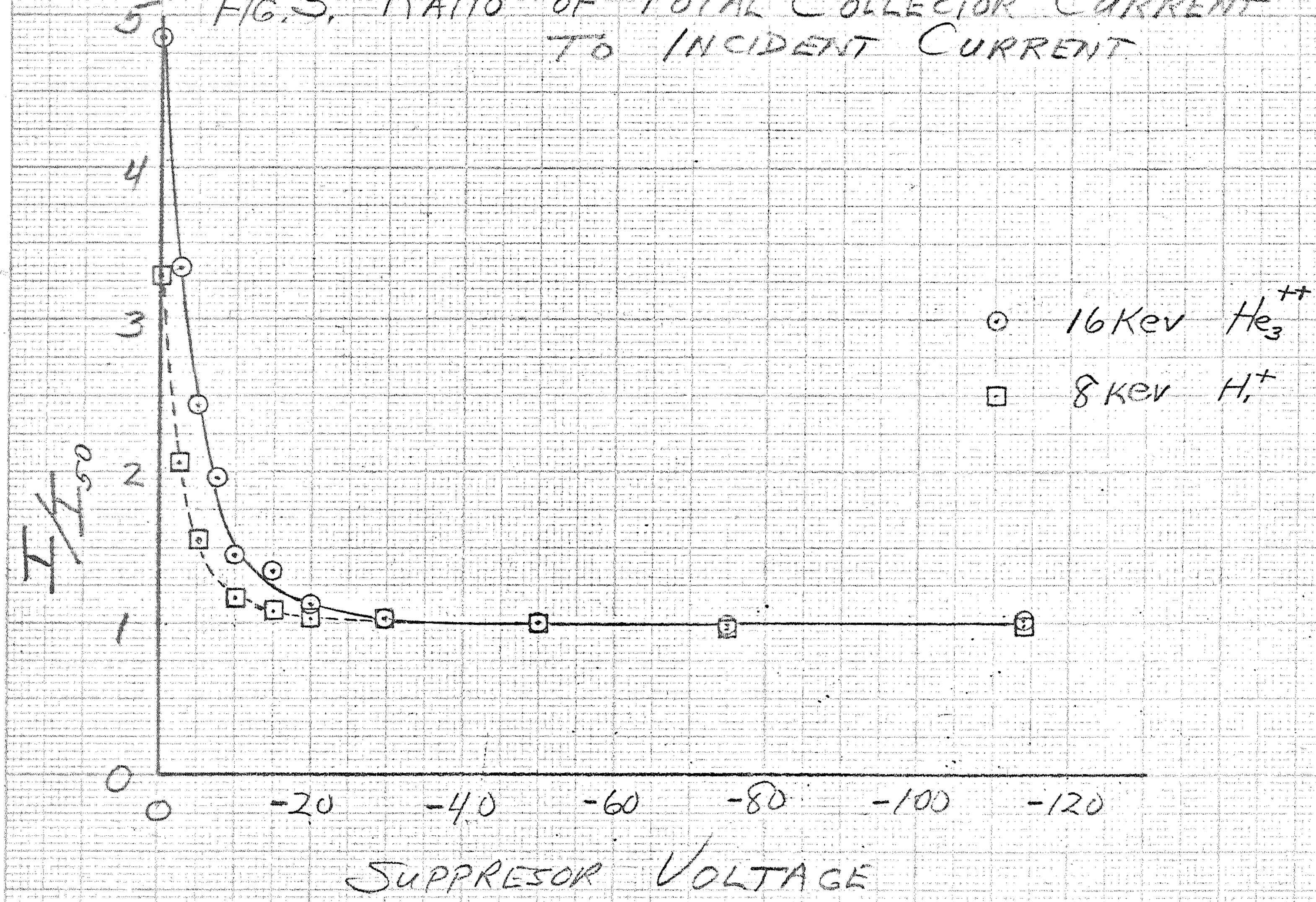
Figure 2
Photograph of Experimental Equipment

FIG. 3, RATIO OF TOTAL COLLECTOR CURRENT TO INCIDENT CURRENT



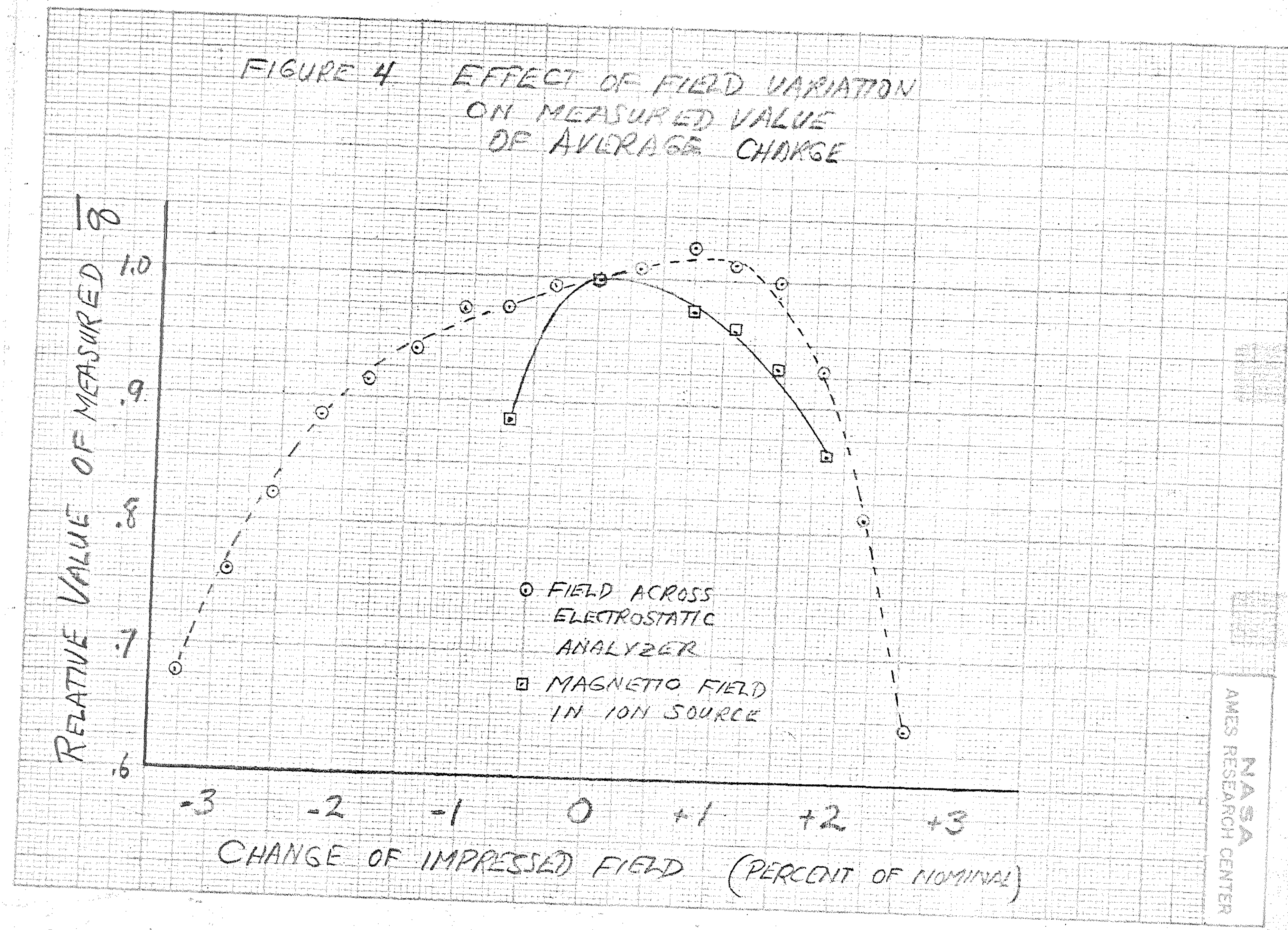


FIGURE 4 EFFECT OF FIELD VARIATION
ON MEASURED VALUE
OF AVERAGE CHARGE
RELATIVE VALUE OF MEASURED
1.0
.9
.8
.7
.6
-3
-2
-1
0
+1
+2
+3
CHANGE OF IMPRESSED FIELD (PERCENT OF NOMINAL)
FIELD ACROSS
ELECTROSTATIC
ANALYZER
MAGNETIC FIELD
IN ION SOURCE
NASA
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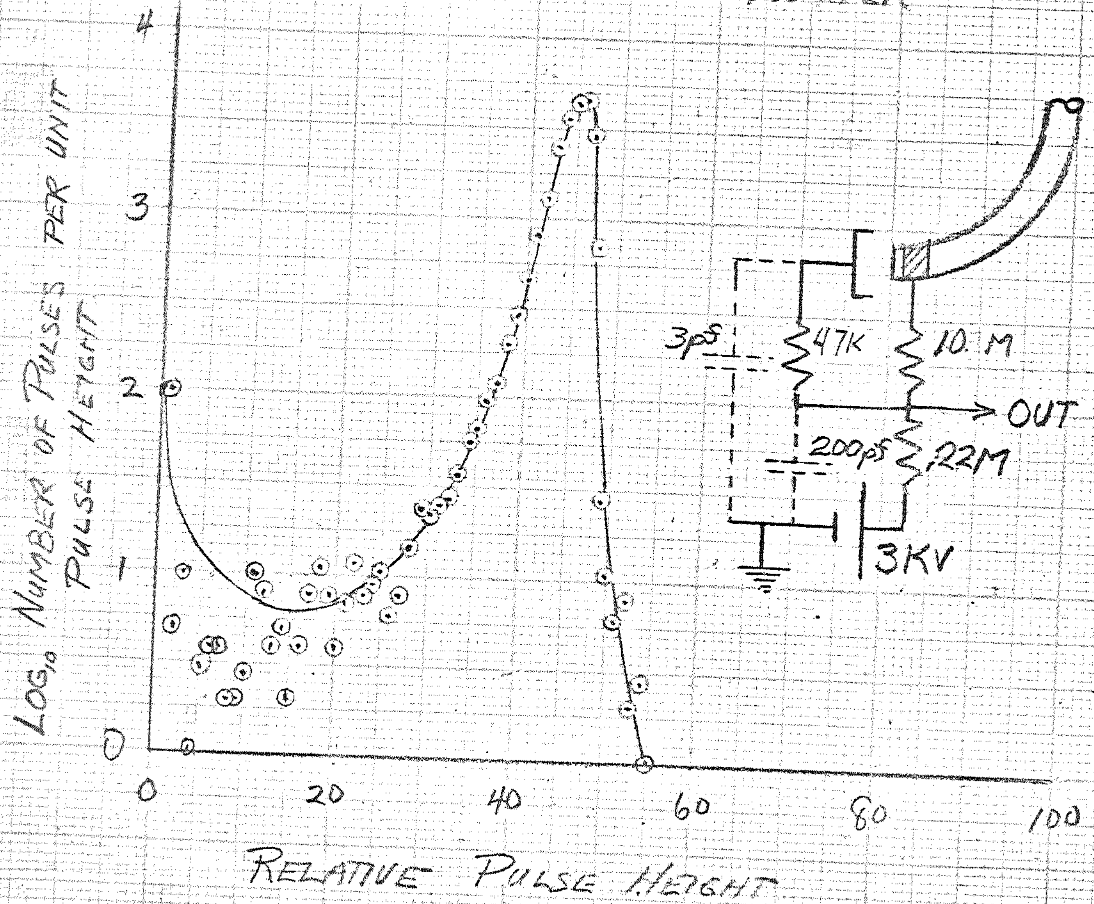
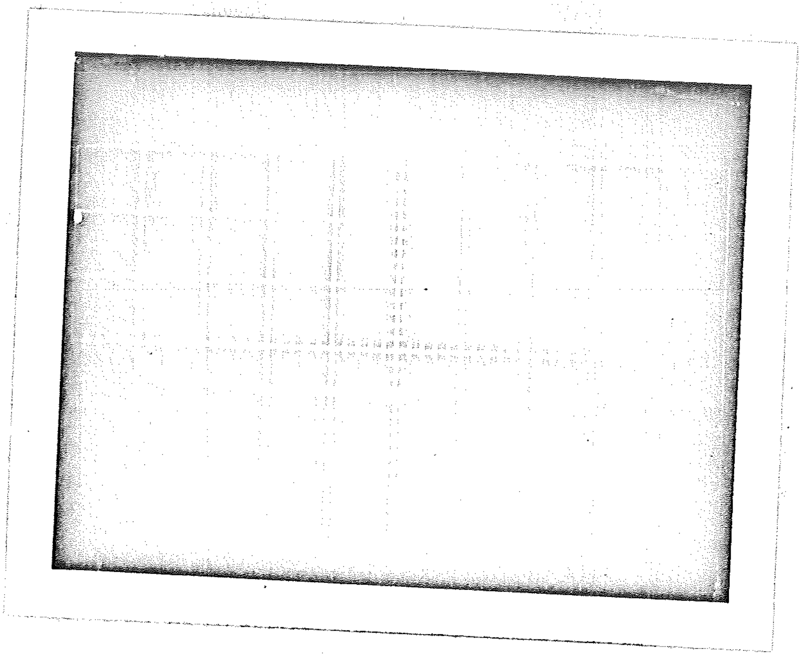
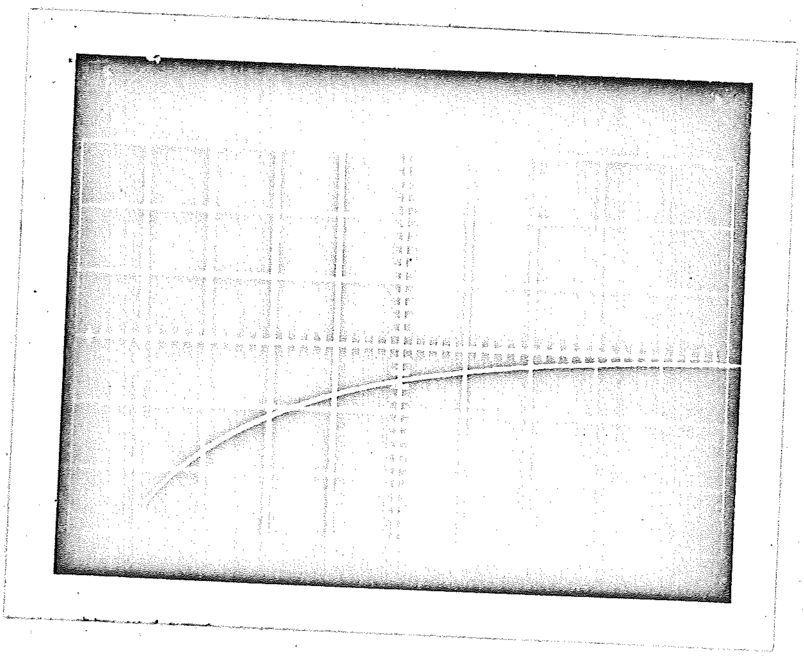
FIG 5 PULSE HEIGHT DISTRIBUTION FOR CONTINUOUS CHANNEL ELECTRON MULTIPLIER





a) PULSE RISE .01 VOLT/DIV VERT, .1 μSEC/DIV HORIZ.



b) PULSE DECAY .01 VOLT/DIV VERT; 20 μSEC/DIV HORIZ.

FIG. 6. OUTPUT PULSE FROM CONTINUOUS CHANNEL ELECTRON MULTIPLIER

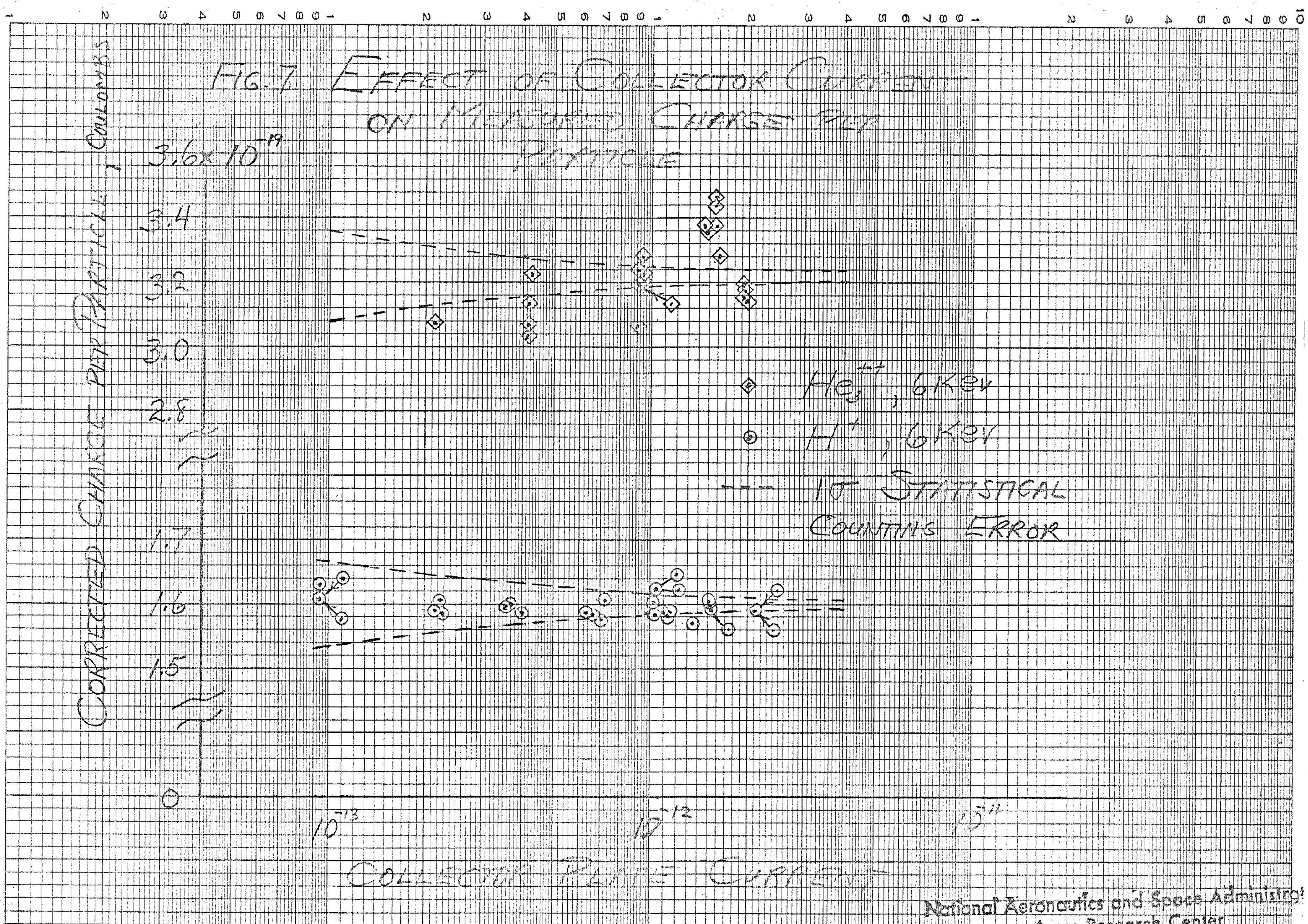


FIG. 7. EFFECT OF COLLECTOR CURRENT ON MEASURED CHARGE PER PARTICLE
CORRECTED CHARGE PER PARTICLE, COULOMBS
3.6x10^-19
3.4
3.2
3.0
2.8
1.7
1.6
1.5
0
He++, 6Kev
H+, 6Kev
1σ STATISTICAL COUNTING ERROR
10^-13
10^-12
10^-11
COLLECTOR PLATE CURRENT

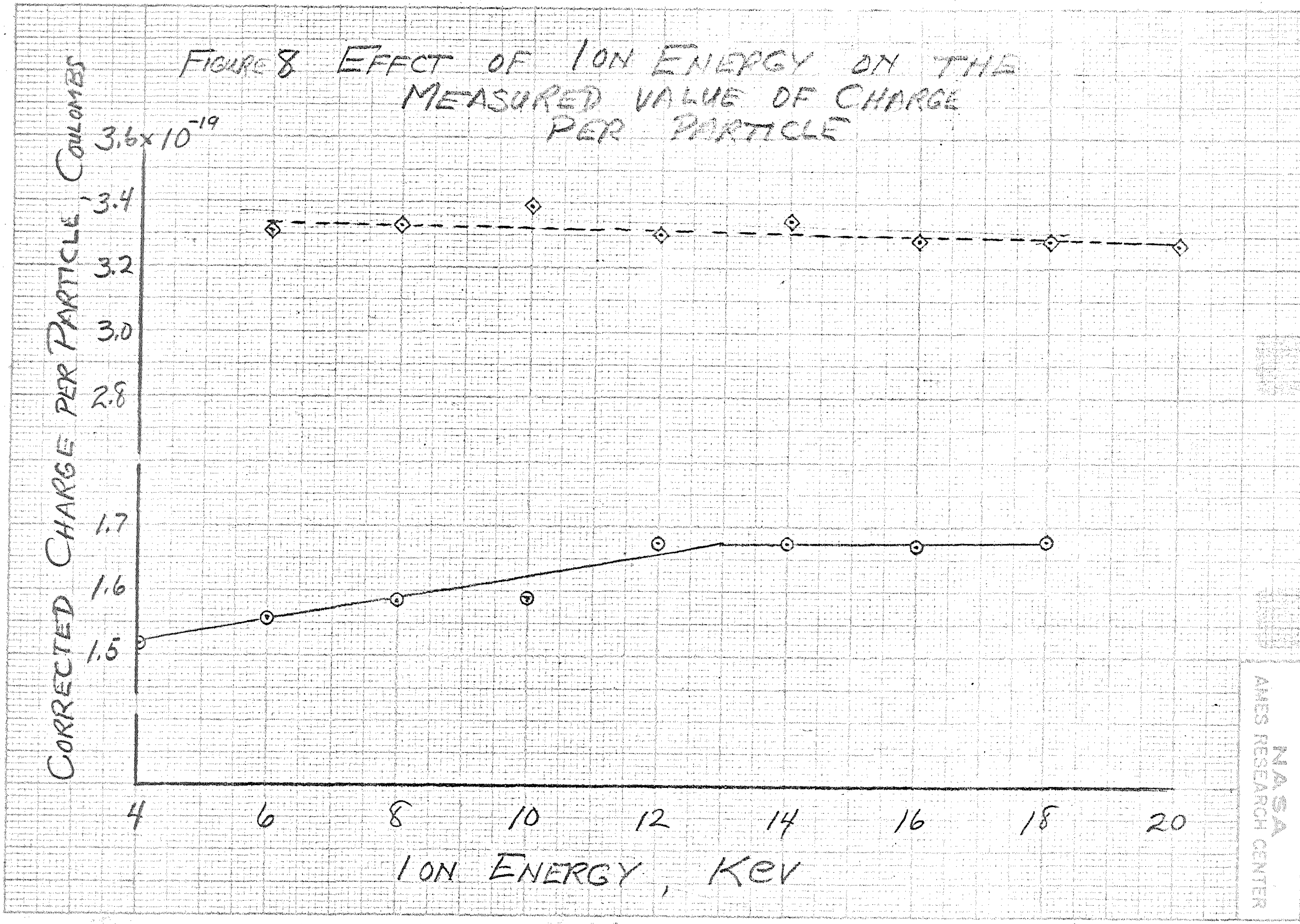


FIGURE 8 EFFECT OF ION ENERGY ON THE MEASURED VALUE OF CHARGE PER PARTICLE
CORRECTED CHARGE PER PARTICLE, COULOMBS
3.6×10^-19
3.4
3.2
3.0
2.8
1.7
1.6
1.5
4
6
8
10
12
14
16
18
20
ION ENERGY, KEV